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Analysis of Alaskan burn severity patterns using remotely sensed data

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Abstract. Wildland fire is the dominant large-scale disturbance mechanism in the Alaskan boreal forest, and it strongly influences forest structure and function. In this research, patterns of burn severity in the Alaskan boreal forest are characterised using 24 fires. First, the relationship between burn severity and area burned is quantified using a linear regression. Second, the spatial correlation of burn severity as a function of topography is modelled using a variogram analysis. Finally, the relationship between vegetation type and spatial patterns of burn severity is quantified using linear models where variograms account for spatial correlation. These results show that: 1) average burn severity increases with the natural logarithm of the area of the wildfire, 2) burn severity is more variable in topographically complex landscapes than in flat landscapes, and 3) there is a significant relationship between burn severity and vegetation type in flat landscapes but not in topographically complex landscapes. These results strengthen the argument that differential flammability of vegetation exists in some boreal landscapes of Alaska. Additionally, these results suggest that through feedbacks between vegetation and burn severity, the distribution of forest vegetation through time is likely more stable in flat terrain than it is in areas with more complex topography.

Additional keywords: Alaska fire, fire variograms, normalised burn ratio, spatial ANOVA.

Introduction

Fire is the dominant disturbance agent in the boreal forest of interior Alaska. As a consequence, the spatial distribution of vegetation across the landscape is a mosaic of previous burns and subsequent secondary succession (Zackrisson 1977; Payette 1992). The link between fire and vegetation is one of the motivating factors for the characterisation of the frequency and size distributions of fires (Yarie 1981; Mann and Plug 1999; Kasischke *et al*. 2002). During large fire years, relatively few fires typically account for the majority of the area burned. However, during these large fire years, there are not only larger fires but a greater number of fires as well (Kasischke *et al*. 2002). Ultimately, the inter-annual variability of area burned in Alaska is driven by large-scale ocean–atmosphere circulation patterns and their influence on weather (Duffy *et al*. 2005). This results in significant variability of the fire regime on both spatial and temporal scales (Johnson 1990; Johnson and Wowchuk 1993; Bessie and Johnson 1995; Kasischke *et al*. 2002). Specifically, the mean and variability of the fire size distribution in a given year change as a function of the total area burned.

Despite its role as a keystone disturbance, some aspects of the fire regime of the Alaskan boreal forest are still poorly understood. Foremost among these, is burn severity, which plays a critical role in the key ecosystem process of secondary succession (Chrosciewicz 1974; Dyrness and Norum 1983; Van Cleve and Viereck 1983; Zasada *et al*. 1983; Foster 1985; Payette 1992; Johnstone *et al*. 2004; Lecomte *et al*. 2005). Previous studies of burn severity in boreal forests have resulted in different metrics for burn severity: from the amount of organic matter consumed to the amount of the soil surface and vegetation that is charred (Michalek *et al*. 2000; Miyanishi and Johnson 2002; Greene *et al*. 2004; van Wagtendonk *et al*. 2004; Epting and Verbyla 2005; Johnstone and Kasischke 2005). Important ecological processes (e.g. post-fire succession and carbon cycling) are differentially influenced depending on the specific characterisation of burn severity. For example, if carbon release from fire is the variable of interest, then the amount of organic matter consumed is an appropriate metric to use for burn severity (Michalek *et al*. 2000). If, however, it is of interest to characterise the relationship between burn severity and post-fire succession, then the post-fire condition of the organic layer including the amount of the soil surface that is charred may be a more appropriate metric of burn severity (Lecomte *et al*. 2005). This works focuses on the metric of burn severity that most likely influences subsequent patterns of secondary succession.

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Many of the factors that drive post-fire succession are strongly related to topography (e.g. water availability for seedlings, solar radiation and burn severity); hence patterns of burn severity need to be characterised across a large spatial domain (Bridge and Johnson 2000). Specifically, the existence of patterns of burn severity associated with different positions on the landscape (Miyanishi and Johnson 2002) provides additional motivation for the quantification of burn severity across large spatial domains that sufficiently represent the range of topographic diversity. The first step towards a better understanding of the relationship between large-scale patterns of burn severity and vegetation dynamics is through the development of statistical models and hypothesis tests. In order to accomplish this, it is essential that the metric of burn severity used be able to estimate burn severity across large spatial domains. In this paper we use single scene post-fire imagery from the Landsat TM to compute the Normalized Burn Ratio (NBR) (Key and Benson 2004) and evaluate large-scale patterns of burn severity at three spatial resolutions (90 m, 500 m and 1 km). The use of a remotely sensed index allows for the burn severity to be quantified at multiple spatial resolutions across large spatial domains.

Methods

Overview

The goal of this work is to characterise several critical aspects of fire–vegetation interactions across interior Alaska. This is accomplished by testing three hypotheses: 1) Average burn severity is not significantly correlated with the size of the wildfire, 2) There is no significant difference in the variability of burn severity for fires that burn in topographically complex landscapes *v.* fires that burn in flat landscapes, and 3) The relationship between burn severity and vegetation type does not change as a function of topography.

Each of these hypotheses is tested by utilising a remotely-sensed measure of burn severity, known as the Normalized Burn Ratio (NBR) (Key and Benson 2004). The NBR is computed using the near and the mid-infrared portions of the electromagnetic spectrum (bands 4 and 7 of the Landsat TM and ETM+ sensors, respectively) (Eqn 1).

$$NBR = \frac{(B_4 - B_7)}{(B_4 + B_7)} \tag{1}$$

NBR was chosen over several other published methods for mapping burn severity due to the fact that it outperformed twelve other remotely-sensed indices when tested on fires in interior Alaska (Epting *et al*. 2005). Specifically, NBR had the highest correlation to field measurements of burn severity. Properties of both vegetation and moisture are radically altered following a burn and NBR is sensitive to these changes since it utilises both the near-infrared channel, which is sensitive to living vegetation, as well as the mid-infrared channel, which is sensitive to moisture.

There are additional benefits of working with remotely-sensed data for studies of burn severity. First, the data are plentiful and cheaper to acquire than field-based methods. An entire burned region can typically be analysed with a single satellite image, thereby generating tens of thousands of data points for a very low cost. Additionally, many areas of interior Alaska have no road access and are therefore difficult to access. Finally, due to the long-running nature of the Landsat program, it is possible to study fires dating back to the mid 1980s using the same methodology presented here. Hence, this work provides a standardized and consistent method to analyse fires and make comparisons across both the spatial and temporal dimensions.

Data assembly and preparation

Landsat TM data were obtained for 24 wildfires (Table 1) that burned across interior Alaska between 1994 and 2002. Details regarding the Landsat scenes are presented in Table 1. The primary limitation for data availability is the existence of cloud-free imagery within one or two years following a burn. Both Landsat TM and ETM+ imagery were utilised in the analysis. All images were processed at a spatial resolution of 30 m, projected to the UTM coordinate system, and converted to at-satellite reflectance before calculating NBR values. Fire perimeters were outlined via onscreen digitizing and provided the boundary for all further analyses.

Existing vegetation maps were compiled to characterise the relationship between pre-fire vegetation and burn severity. The vegetation maps are publicly available datasets created by state and federal agencies and were generated using Landsat MSS, Landsat TM, and SPOT MSS data. Seven datasets were combined, such that only those vegetation classes shared by all seven maps were included in the analysis. The final combined map was resampled at a resolution of 30 m to match the resolution of the NBR product. Vegetation classes used in this analysis included 1) closed conifer, 2) open conifer, 3) broadleaf forest, 4) shrub, and 5) herbaceous communities.

The definition of vegetation classes in interior Alaska is well established and generally follows the guidelines of Viereck *et al*. (1992). Closed conifer forest includes black and white spruce (*Picea mariana* and *Picea glauca*, respectively) stands characterised by at least 25% cover. Open conifer also contains black and white spruce, but the trees represent only 10–25% total cover. Broadleaf forest is characterised as a stand consisting of more than 75% broadleaf trees, such as quaking aspen (*Populus tremuloides*), paper birch (*Betula papyrifera*), and balsam poplar (*Populus balsamifera*). The shrub class is dominated by shrubs and contains less than 10% tree cover, whereas the herbaceous class contains no more than 25% shrub cover and less than 10% tree cover.

The 30 m NBR and vegetation data were aggregated to 90 m, 500 m and 1 km spatial resolutions. When aggregating from finer to more coarse spatial resolution, the mean value was used for the NBR calculations, which are continuous data, while the mode was used for vegetation classes, which are categorical data. By aggregating the NBR metric and using a mean, the potential for results to be driven by measurement error that can exist in the classification algorithms associated with remotely sensed products is reduced. By performing the analysis at three different spatial resolutions, differences in fire–vegetation dynamics across spatial scales can be examined.

Statistical analyses

Hypothesis 1

Average burn severity is not significantly correlated with the natural logarithm of the area of the wildfire. The relationship

Table 1. Results from spatial ANOVA at multiple resolutions

Variograms were fit to model spatial correlation and then restricted maximum likelihood (REML) was used to estimate parameters in a spatial ANOVA model. The p-value from the spatial ANOVA corresponds to a test of the hypothesis that the average burn severity is equal for each vegetation class in a given fire. Superscripts for 'spatial ANOVA p-value' indicate that not all forest vegetation classes were used in the analysis for a given fire due to insufficient data (e.g. deciduous data were insufficient for the Tolovana West fire). – not enough data; NS = not significant at the 0.05 level

Fire name	Year	Area (ha)	Landsat TM info			Spatial ANOVA p-value			Terrain class
			Date	Path	Row	90 m	500 m	1 km	
Tolovana West	2000	308	8/16/2000	70	14	NS[A]	–	–	Hill/Mtn
Chatanika	1999[D]	400	8/16/2000	70	14	NS	–	–	Hill/Mtn
Minto	1999	1,242	8/16/2000	70	14	0.01[A]	NS[A]	–	Flat
Tolovana East	2000	1,344	8/16/2000	70	14	0.01	–	–	Flat
Forty Mile	1998	2,340	8/4/1999	64	16	NS	–	–	Hill/Mtn
Taylor Hwy	1999	2,643	8/4/1999	64	16	NS	–	–	Hill/Mtn
Laude River	1999	3,110	8/4/1999	64	16	NS	NS[A]	–	Hill/Mtn
Toklat East	2000	3,889	7/21/2002	70	15	NS	NS[C]	–	Hill/Mtn
Square Lake	2002	6,583	7/21/2002	70	15	NS	NS[A]	–	Hill/Mtn
Toklat West	2000	6,898	7/21/2002	70	15	0.00	–	–	Flat
Chena	1999	7,584	8/16/2000	70	14	NS	NS	–	Hill/Mtn
Webber Creek	1993	7,975	6/11/1994	66	14	NS	NS[A]	NS[A]	Hill/Mtn
Gardiner Creek	1998	11,559	8/4/1999	64	16	NS	NS	NS[A]	Hill/Mtn
Prindle Volcano	1998	13,998	8/4/1999	64	16	NS[A]	NS[A]	NS[A]	Hill/Mtn
Kantishna	2000	15,451	7/21/2002	70	15	0.00[A]	NS[A]	NS[A]	Flat
Yukon West	1999	17,862	9/10/1999	67	14	NS[A]	NS[A]	–	Hill/Mtn
Yukon 242	1999	18,907	9/10/1999	67	14	NS	NS	–	Hill/Mtn
Yukon 260	1999	19,676	9/10/1999	67	14	NS	NS[B]	–	Hill/Mtn
Yukon East	1999	19,737	9/10/1999	67	14	0.07	0.10	–	Hill/Mtn
Fish Creek	2001	27,831	7/21/2002	70	15	0.00	0.00	0.02[A]	Flat
Twin Lakes	2002	29,617	7/21/2002	70	15	0.00	0.00[A]	0.00[A]	Flat
Survey Line	2001	44,445	7/21/2002	70	15	0.00	0.00	0.00	Flat
Bear Lake	2000	61,670	6/16/2000	70	15	0.00	0.00	0.00	Flat
Paddle Creek	1993	93,655	6/11/1994	66	14	0.02	0.00	NS[A]	Flat

A = closed conifer *v.* open conifer, B = closed conifer *v.* broadleaf, C = open conifer *v.* broadleaf, D = date is estimated.

between the average NBR and the area burned by a fire is modelled using a linear regression. Average NBR was computed for each fire and then regressed on the natural logarithm of area burned. In order to assess sensitivity of the results to potentially influential points, a cross-validation was performed. For each of the 10,000 iterations of the cross-validation, three randomly selected fires were excluded and the regression parameters were re-estimated. From each of these 10,000 regression models, there is a corresponding p-value. From this list of 10,000 p-values, the median was used to assess the results of the cross-validation. This test was only performed at the 90 m spatial resolution because the average NBR for a fire is relatively invariant to the size of the pixels within the fire used to compute the average.

Hypothesis 2

There is no significant difference in the variability of burn severity for fires that burn topographically complex landscapes *v.* fires that burn in flat landscapes.

The terrain over which each fire burned was categorized *a priori* as either 1) flat or 2) hilly/mountainous. The criteria for topographic characterisation was based on the mean slope value of the entire burned region. This includes all pixels within the burn perimeter. Slopes were derived from a digital elevation model of the entire state of Alaska, at a spatial resolution of 300 m. Any fire with an average slope greater than 1.5 degrees was classified as hilly/mountainous. Of the 24 fires, nine occurred on flat terrain and 15 occurred on hilly/mountainous terrain. In order to assess differences in the spatial correlation structure of fires burning in different topography, a variogram analysis was performed. Variograms can be used to characterise changes in the spatial correlation of a variable (e.g. NBR) as a function of distance. In this application, the variogram quantifies the similarity of NBR values as a function of distance between pixels. Variograms can be computed using the following formula (Eqn 2)

$$\gamma(d_1 - d_2) = \left(\frac{1}{2}\right) \mathrm{var}(Z(d_1) - Z(d_2)) \qquad (2)$$

where Z is a random spatial process (NBR in this example), and d_i in this case represents a unique location in 2-D space. The difference between two d_i's is computed as the sum of the squared distances of both the horizontal and vertical component. This variogram analysis was performed using the geoR package (Ribeiro and Diggle 2001) in the R statistical computing language.

In order to assess differences in the spatial correlation structure of burn severity as a function of topography, a 'composite' variogram was calculated for fires burning in both flat and hilly/mountainous terrains. The composite variogram is the weighted average of the empirical variograms from each fire within the topographic class. These two composite variograms each represent an average of the empirical variograms for the respective topographic categories (i.e. flat or hilly/mountainous). The difference between the two composite variograms was quantified by taking the sum of the squared differences between the empirical variograms (Eqn 3).

$$D = \sum_{i=1}^{n} (\gamma_{flat}(i) - \gamma_{hilly}(i))^2 \quad (3)$$

where γ is defined as in Eqn 2, and n is the number of bins in the empirical variogram. Hence, the difference between these two composite variograms is mapped to a single value (Eqn 3). The null distribution of the test statistic 'D' was simulated by discarding the original topographic information and randomly dividing the variograms into two groups. Once the fires are randomly divided into two groups of size nine and 15 (identical to the respective number of fires from each topographic category in the original dataset) the value of the test statistic is recalculated. This produces a realisation from the distribution of this test statistic under the null hypothesis that there is no difference between the composite variograms for the two topographic categories. This process was repeated 10,000 times to generate 10,000 realisations of the null distribution. Using this distribution, and the observed value of the test statistic (Eqn 3), a p-value for the test of the null hypothesis, 'There is no difference between the spatial correlation structure of burn severity for fires burning in flat *v.* hilly/mountainous terrain' is computed. Comparison of composite variograms for flat *v.* hilly/mountainous terrain was performed at all three spatial resolutions.

Hypothesis 3

The relationship between burn severity and vegetation type does not change as a function of topography. Linear models were fit to quantify the relationship between burn severity and vegetation type. In this portion of the analysis, only the three forest vegetation classes are used: closed conifer, open conifer, and broadleaf. The shrub and herbaceous classes were eliminated in order to simplify the interpretation of the ANOVA analysis, to focus on the differences between burn severities of forest types, and to only use vegetation classes with enough data to yield a meaningful analysis.

The first step in this analysis is to fit a simple ANOVA model where no spatial correlation is taken into account. In this ANOVA model, the response variable is burn severity and the forest types: closed conifer, open conifer, and broadleaf are levels of the factor 'vegetation type'. If the p-value corresponding to the test of the equality of the NBR across vegetation types is significant for this simple ANOVA, then a more sophisticated model that accounts for spatial correlation is fit. The impact of the explicit inclusion of the spatial correlation in the linear model is an increase in the estimate of the variability associated with the parameter estimates in the model. This increase in variability results in smaller test statistics and larger p-values. Hence, if in the presence of significant spatial correlation, the non-spatial ANOVA model has a non-significant p-value, the incorporation of a spatial component will usually result in a larger and hence less significant p-value.

The application of the spatial ANOVA begins with a second test. This test deals with the similarity of the correlation structure between vegetation classes within each fire. For each fire, differences in the spatial correlation of burn severity between forest vegetation classes were assessed by considering the closed conifer forest as a baseline and pooling the open conifer and broadleaf forest into a separate single category. The closed conifer was used as a baseline since it is the most common; hence this provides results for the greatest number of fires. The test for differences in the spatial correlation of vegetation classes (i.e. the variograms) was performed using the re-sampling method detailed under hypothesis 2. If the results of this test were significant, then a spatial ANOVA model that allows for a distinct correlation structure for each of the different forest vegetation classes was fit. Otherwise, a spatial ANOVA with a single correlation structure across forest vegetation classes was fit. In either case, the resulting model allows for estimation of the differences in average NBR within a given fire for the three forest vegetation types. This is essentially an ANOVA model where the lack of independence is accounted for through the construction of a separate variogram model for each vegetation type. The parameters in the ANOVA model are estimated using restricted maximum likelihood estimation (REML) (Smyth and Verbyla 1996).

At a given spatial resolution, each fire must have twenty-five cells for each forest vegetation class included in the analysis. Twenty-five was selected arbitrarily, but provided a balance between robustness of results and the number of fires that were able to be used in this analysis. If fewer than twenty-five cells of a vegetation class were present in a given fire, that vegetation class is omitted from the analysis of that fire at that spatial resolution (Table 1). At the 90 m spatial resolution some of the fires were analysed through resampling due to the large size of the datasets. At the 500 m and 1 km spatial resolutions, the size of the datasets is such that a single analysis using the entire dataset was tractable.

Results

Hypothesis 1

Average burn severity is not significantly correlated with the natural logarithm of the area of the wildfire. The linear regression of average NBR on the natural logarithm of area burned provides a test of the null hypothesis that there is no relationship between average NBR and area burned. As values of the NBR become more negative, the severity of the burn increases. The analysis was performed using 24 fires from across interior Alaska (Fig. 1 and Table 1). With a p-value of 0.02 there is sufficient evidence to reject this hypothesis and conclude that larger fires have a higher average burn severity. These results suggest there is a moderately strong linear relationship between the natural logarithm of the size of a fire and the average burn severity (Fig. 2). Based on this regression model we expect that for every unit increase in the logarithm of fire size, there is a corresponding decrease of 51 in the average NBR associated with that fire. Large fires are more likely to contain areas that are more severely burned than smaller fires as opposed to a uniform increase in overall burn severity (Fig. 3). This difference was quantified using the non-parametric quantile test ($P < 0.0001$) at the 80th quantile (Johnson *et al*. 1987).

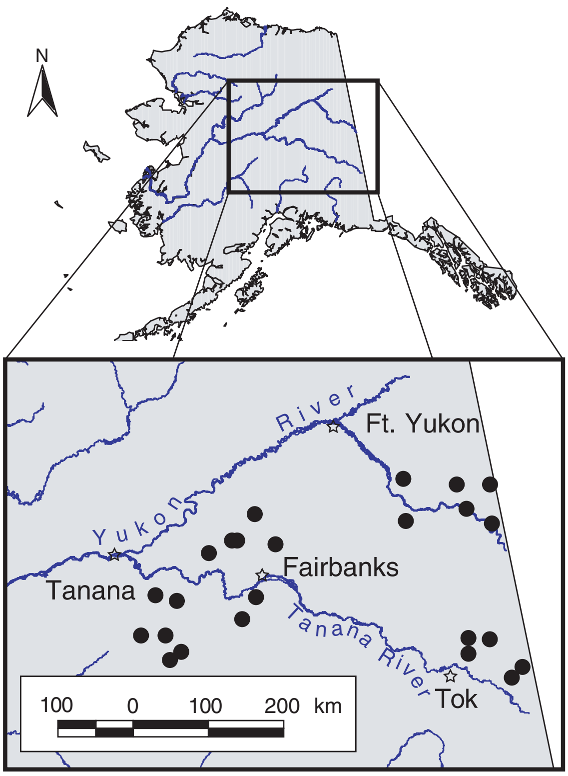

Fig. 1. Locations of the 24 fires used in this analysis.

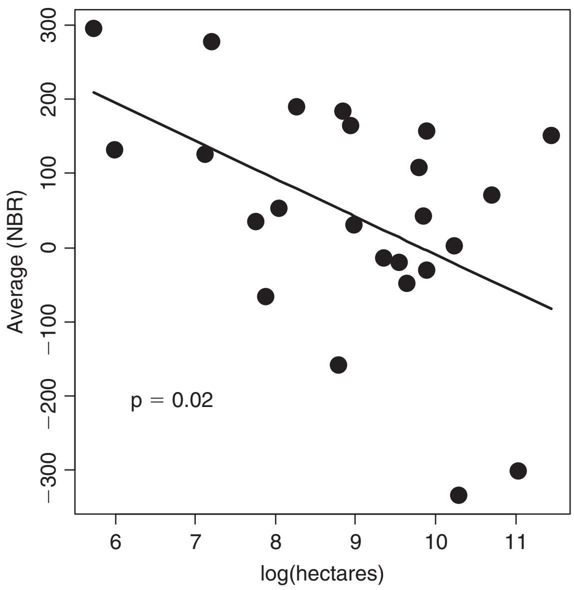

Fig. 2. Scatterplot and line corresponding to regression of average normalized burn ratio (NBR) on the natural logarithm of hectares burned. Negative values of NBR correspond to more severe burning. The equation for the regression line is NBR = 501.9 − 51.1(log(hectares)). R-squared = 0.24. Cross-validation was performed where three randomly selected fires were excluded from the analysis and the regression parameters were re-estimated using the randomly selected subset. This was repeated 10,000 times giving a median p-value of 0.02.

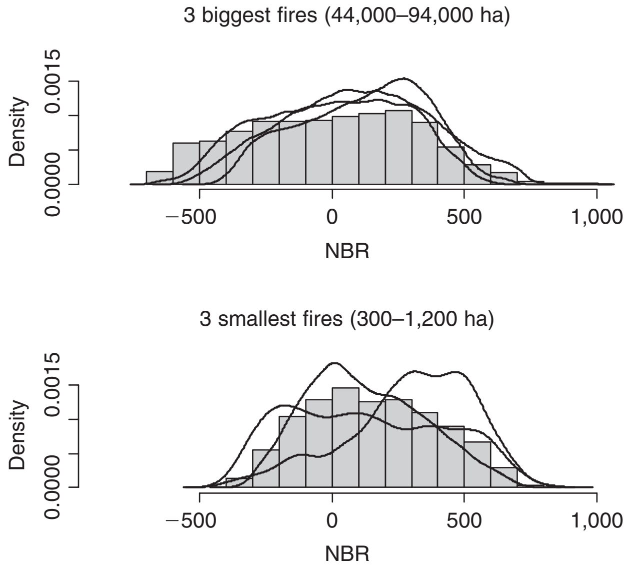

Fig. 3. Histograms and density estimates for the three biggest and three smallest fires analysed. Histograms represent pooled data and density estimates (lines) correspond to individual fires. Comparison of the pooled histograms for the biggest and smallest fires shows that the largest fires contain subregions that burn more severely (large negative values of NBR) than any region within the smallest fires. This difference was quantified using the non-parametric quantile test ($P < 0.0001$) at the 80th quantile (Johnson *et al.* 1987).

Hypothesis 2

There is no significant difference in the variability of burn severity for fires that burn in topographically complex landscapes *v.* fires that burn in flat landscapes. At the 0.1 level, there is a significant difference in the composite variograms of NBR between fires that burn on flat and hilly/mountainous terrain (Fig. 4) for the two larger spatial resolutions (500 m: $P = 0.1$ and 1 km: $P = 0.1$). However, there is not a significant difference at the 90 m resolution (90 m: $P = 0.25$). The direction of difference was consistent across all spatial resolutions and fires burning in the flats have a higher degree of spatial correlation across a range of distances.

Hypothesis 3

The relationship between burn severity and vegetation type does not change as a function of topography. At the 90 m resolution, only one of the 15 (7%) hilly/mountainous fires indicate a difference in burn severity across vegetation classes, whereas all nine of the flat terrain fires indicate such differences (Table 1). At the 500 m resolution, enough data were available to perform this analysis for 18 of the 24 fires. Of the 11 hilly/mountainous fires, only one (or 9%) indicated differences in burn severity across vegetation classes, whereas five of the seven (or 71%) of the flat terrain fires indicated such differences (Table 1). At the 1 km resolution, enough data were available to perform this analysis on nine fires. None of the three fires in the hilly/mountainous terrain indicated a difference in burn severity across vegetation classes, whereas four of the six (66.7%) flat terrain fires indicated such differences (Table 1). In general, regardless of scale,

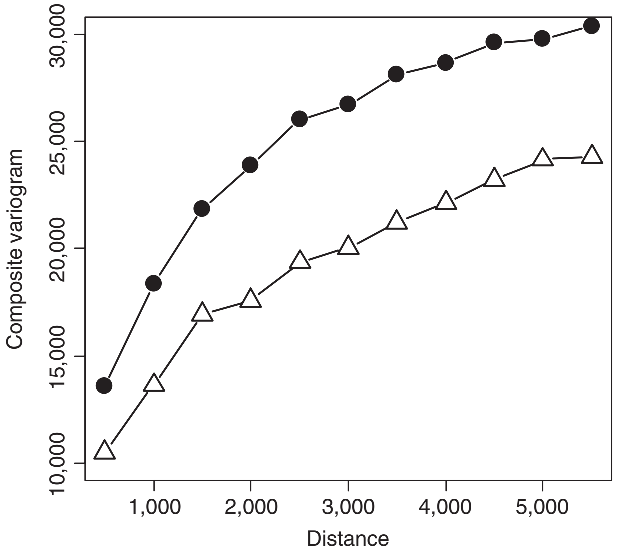

Fig. 4. Composite variograms for burn severity as measured by normalized burn ratio (NBR) of fires that burn on both flat (shown as triangles) and hilly/mountainous (shown as circles) terrain were compared at 90 m, 500 m and 1 km spatial resolutions. The difference between variograms was marginally significant for the 500 m and 1 km resolution (500 m: $P = 0.10$ and 1 km: $P = 0.10$), while there was no statistical significance at the 90 m resolution ($P = 0.25$). Results shown here are for the 1 km resolution.

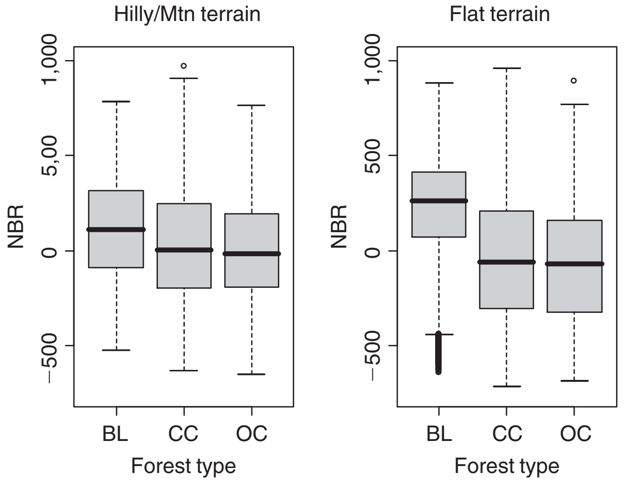

Fig. 5. Boxplots of the normalized burn ratio (NBR) by forest type for two classes of terrain complexity across all twenty-four fires. Horizontal black lines represent the median. Boxes extend to the 25th and 75th percentile. Whiskers extend to the most extreme data point, which is no more than 1.5 times the interquartile range from the box. Negative values of NBR correspond to more severe burning. In general, the Open Conifer (OC) has the most severe burning, the Closed Conifer (CC) has similar but less severe burning, and the Broadleaf (BL) class has the least severe burning. In the flat terrain the Broadleaf forest type is more likely to be significantly different than the others (Table 1).

the difference in burn severity, as a function of vegetation type is considerably higher for fires that burn on flat terrain (Fig. 5).

Discussion

Conceptual model of the boreal forest

At large spatial scales, the boreal forest can be conceptualized as a system dominated by the spatially explicit interacting components of weather, fire and forest vegetation type. With respect to fire and weather, atmospheric teleconnections and monthly weather explain roughly three quarters of the observed inter-annual variability in area burned over the past five decades (Duffy *et al.* 2005). This work further refines the conceptual model through tests of hypotheses that characterise and quantify fire–vegetation interactions across several spatial scales within interior Alaska.

Our results show a significant relationship between the size of a fire and average burn severity (Fig. 2). Since the fire size distribution in a given year changes as a function of the total area burned, differences in fire–vegetation interactions that exist as a function of fire size likely play an important role in the determination of forest structure through impacts on succession. Specifically, this result suggests a possible link between fire size and successional trajectory, through the impacts of burn severity on succession (Johnstone *et al.* 2004). Since larger fires are associated with more severe burning (more negative NBR) due to the existence of subregions within large fires that burn at a level of severity not seen in smaller fires (Fig. 3), years with greater area burned likely correspond to an increase in the diversity of successional trajectories. Given the impact of ocean–atmospheric circulation on annual area burned (Duffy *et al.* 2005), this implies that climatic influences on annual area burned impact succession and carbon cycling vicariously through differential burn severity.

Our results also show that topography significantly influences interactions between fire and vegetation. While it is no surprise that broadleaf vegetation has a lower average burn severity than coniferous vegetation, our results are the first to show that this relationship is more pronounced in flat terrain (Fig. 5, Table 1). In conjunction with the impact of burn severity on succession, this result has implications for the role of topography with respect to changes in the dominant forest vegetation. When both broadleaf and coniferous species were present before fire, intermediate burn severities tend to favour the dominance of broadleaf species through asexual re-sprouting (Zasada *et al.* 1983) and more severe burns have been shown to favour post-fire dominance of coniferous species (Johnstone *et al.* 2004). Hence the less severe burns associated with deciduous vegetation in flat terrain seem likely to favour a self-replacement successional trajectory.

We also found that lower spatial correlation of burn severity exists in hilly or mountainous regions, as opposed to the flats where burn severity is more homogeneous (i.e. less variable) (Fig. 4). This is likely a consequence of differential heterogeneity in both species composition (Van Cleve and Viereck 1983) and fire behaviour (Van Wagner 1977). Through the link between burn severity and succession, topography influences the heterogeneity of forest vegetation. The relative homogeneity of burn severity in the flats reinforces the implication that self-replacement successional trajectories are more likely in deciduous stands within less topographically complex areas. This does not preclude the same type of 'inertia' from existing in topographically complex regions; however, pattern formation of forest vegetation types in topographically complex regions is more likely to be driven by physiological constraints associated with gradients of solar insolation and moisture (Van Cleve and Viereck 1983).

The fire–vegetation interactions presented here hold for spatial resolutions varying across several orders of magnitude, which has implications for future data collection and analysis. These results also provide critical information for spatially explicit simulation studies of burn severity. Additionally, for tests of hypotheses involving data collected across a large spatial domain, the characterisation of spatial correlation is essential in order to ensure that hypothesis-testing techniques are applied appropriately. Although this work provides specific information regarding the link between burn severity and vegetation for fires that burn in flat terrain, more work needs to be done to characterise the more complex relationship that exist when fires burn in complex terrain.

Burn severity and carbon cycling

The boreal forest covers 12 million square km of the northern hemisphere and contains roughly 40% of the world's reactive soil carbon, an amount similar to that held in the atmosphere (Melillo *et al*. 1993; IPCC 2001). This carbon is vulnerable to release from disturbance and fire plays a critical role in the carbon cycle of boreal forests (Csiszar *et al*. 2004; McGuire *et al*. 2004). Large-scale biogeochemical models have traditionally treated the initial carbon loss in fire as fractions of above-ground and below-ground carbon that are defined regionally as the average of studies that have been conducted in the region (e.g. McGuire *et al*. 2004). The ability to estimate the temporal and spatial variability of initial carbon loss after fire within a region has been limited by knowledge of how initial carbon loss varies in time and space. The results of this study represent progress in helping to define how initial carbon loss varies in time and space. Now that we better understand how a satellite-derived measure of burn severity varies in time and space, an important next step will be to verify how NBR relates to carbon loss after fire. Approximately 10% of the boreal forest in interior Alaska burned during the fire seasons of 2004 and 2005, and several studies are now being conducted to estimate initial carbon loss after fire and are attempting to relate these to NBR. The results of those studies combined with the results of our study should allow large-scale biogeochemical models to better estimate how fire influences carbon cycling within the Alaska boreal forest.

Summary

This characterisation of fire–vegetation interactions across large spatial domains provides critical information for a conceptual model of the Alaskan boreal forest. The results of a linear regression of average burn severity on the natural logarithm of average fire size show that burn severity increases with fire size. Since the fire size distribution in a given year changes as a function of the total area burned, differences in fire–vegetation interactions that exist as a function of fire size likely play an important role in the determination of forest structure through impacts on succession. This coupled with the impact of ocean–atmospheric circulation on annual area burned (Duffy *et al*. 2005), implies that climatic influences on annual area burned impact succession and carbon cycling vicariously through differential burn severity.

We also found that topography plays a critical role in the determination of fire–vegetation interactions. Specifically, we show that broadleaf vegetation has a lower average burn severity than coniferous vegetation, and this difference is more pronounced in flat terrain.

Coupled with the link between burn severity and succession, these topographically mediated differences in burn severity as a function of vegetation type imply that with respect to vegetation distribution, there are stronger feedback mechanisms in the flats as opposed to more topographically complex terrain. This link is supported by our finding that fires burning in the flats have greater spatial correlation (as measured by variogram analysis) of burn severity than those burning in hilly/mountainous terrain. The relative homogeneity of burn severity in the flats reinforces the implication that self-replacement successional trajectories are more likely in deciduous stands within less topographically complex areas.

Collectively these results underscore the importance of fire size and topography as important factors in the determination of fire–vegetation interactions, and strengthen the argument that differential flammability of vegetation plays a significant role in the boreal forest of Alaska. Specifically, the role of fire size and topography as determinants of burn severity underscores their relevance to both carbon cycling and secondary succession. Because of the link between vegetation and burn severity in the flats, fire induced shifts in the dominant forest species in the flats have a greater potential to influence direct carbon emissions than corresponding changes in dominant forest type that occur in more complex topography. This work characterizes the variability of burn severity for fires burning in both flat and complex terrain. However, for fires that burn in complex terrain, there does not appear to be a link between burn severity and vegetation. As a next step, models need to be constructed that examine burn severity as a function of different combinations of slope, aspect, and elevation, in order to characterise spatial patterns of burn severity for fires in complex topography. Future modelling efforts should take into account the role of fire size and topography as modifiers of fire–vegetation interactions.

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